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IMPORTANCE AND PROGRESS OF WIND POWER UTILIZATION IN DENMARK

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IMPORTANCE AND PROGRESS OF WIND POWER UTILIZATION IN DENMARK

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(Continued from No. 15, 5 August 1942, p. 346)

Most of the Danish wind power plants now operating are made by the two companies Lykkegaard and F. L. Smidth. The designs are basically different. While the Lykkegaard plants already have enough operating experience so that the design is fixed, the F. L. Smidth plants are still in development. /370*

Design of the Wind Power Plants

The Lykkegaard wind power plants are manufactured in two patterns, "Folding Sail" and "Aurora", based on the design given by La Cour. The Aurora plant is intended for small electric plants and is built up to a wind wheel diameter of 5.5 m. The Folding Sail (Figure 3) serves to generate power for small national electrical plants. It is equipped with wind wheels of 7 to 18 m diameter and runs relatively slowly. It is primarily the Folding Sail plants with 18 m diameter which are considered for wind power plants which are to feed a network. One other plant with 20 m diameter is also provided for larger power requirement.

The design of the Lykkegaard plant is simple in concept: The sail cross, which corresponds to the design developed by La Cour, is placed on an axle which carries the rotation of the wind wheel through a bevel gear and a shaft to a DC generator on the ground. The rate of rotation cannot exceed a certain value (redirecting equipment). It is directed into the wind by wind vanes at the sides.

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* Numbers in the margins represent pagination in the foreign text.

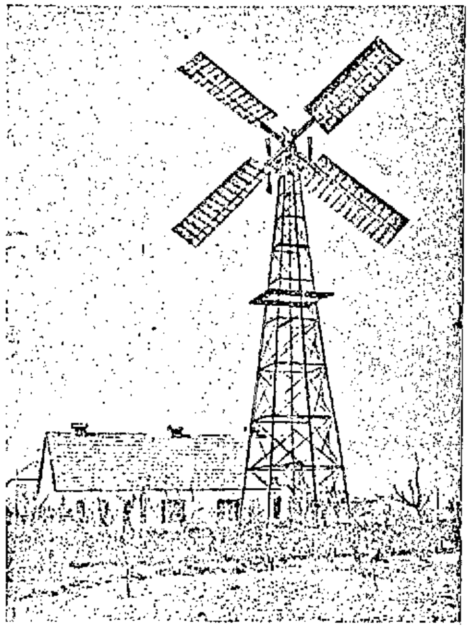

Figure 3. Folding Sail plant, 18 m wind wheel diameter, 30 kW capacity at 10 m/s.

The details of the head can be seen in Figure 4. The sails (F) and their hinges are made of selected wood, with great care for the connecting parts. The sail spars (A) are bolted to a heavy cast iron hub (B) on the axle (C). This axle runs in the two S. K. F. ball bearings (D, E). The flaps of the sail F are mounted on special hinges and connected through the rods (G). These are connected through a system of rods to the control rod (H). The control rod passes through the hollow axle (C) and connects to the system (K – K), which has the counterweight (L) hanging on one leg. This counterweight holds the flaps shut up to a certain wind speed. With increasing wind pressure they are opened, so that the wind wheel cannot exceed a certain arbitrarily adjustable rate of rotation. This redirecting system can also be operated from the foot of the tower. Figure 5 shows a Folding Sail wind power plant in the folded position.

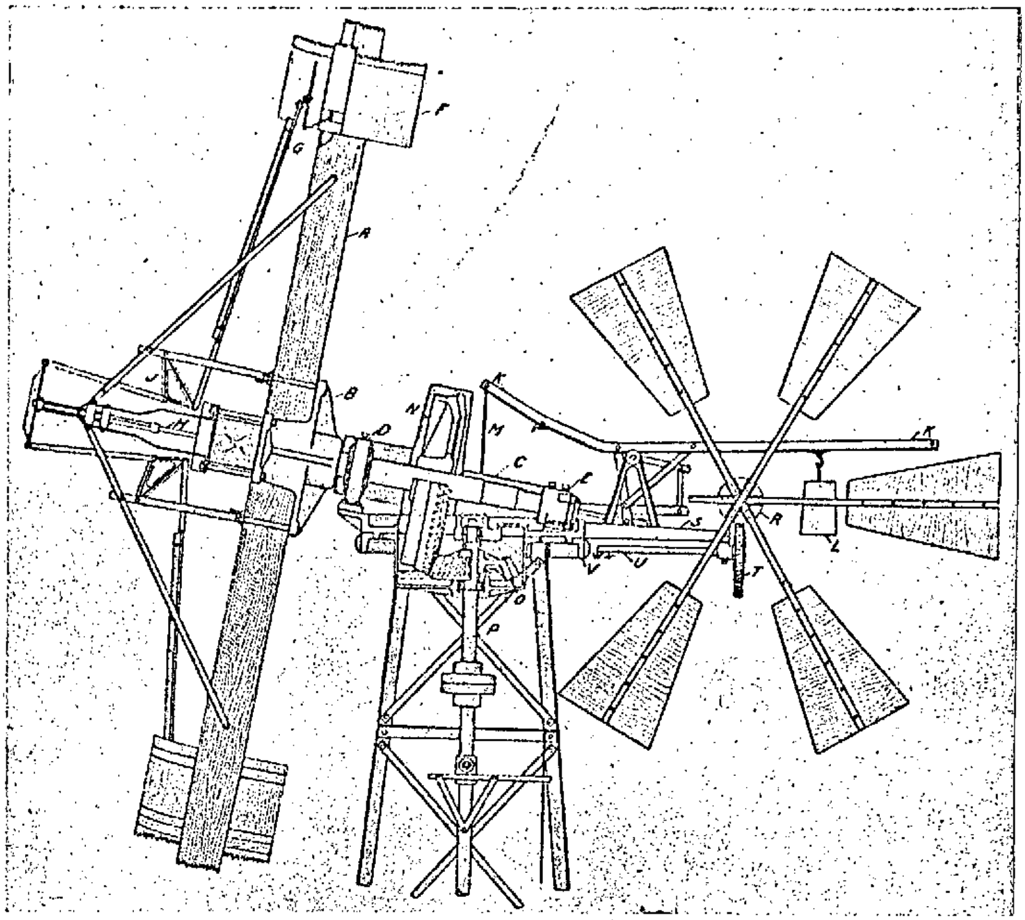

Figure 4. Head of a Lykkegaard wind power plant.

A	Sail spar	G	Rods	N	Bevel gear
B	Cast iron hub	H	Control rod	R	Wind vane
C	Axle (hollow)	K-K	Folding rod	T	Worm wheel
D,E	ball bearings	L	Counterweight	W	Screw
F	Sail				

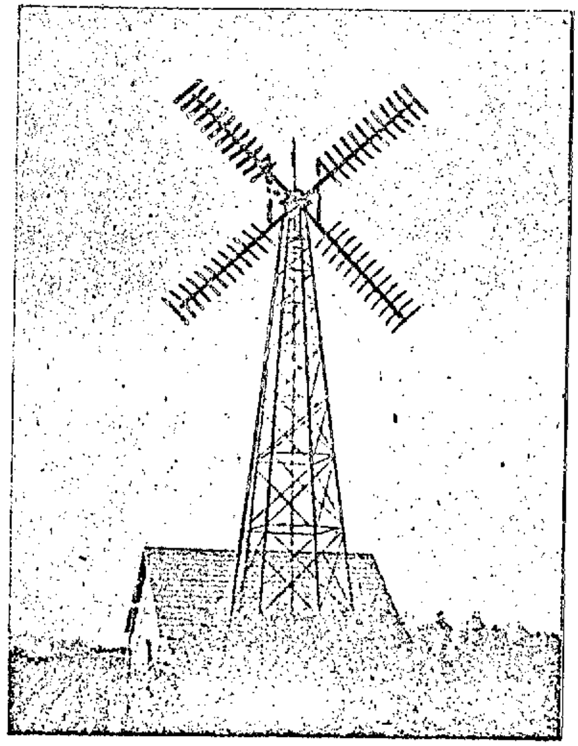

Figure 5. Folding Sail plant in the folded position.

The rotation of the wind wheel axle is transferred through the bevel gear (N) meshing with gear (O) to the vertical shaft. Both gears run in a sealed oil bath. The upper part of the vertical shaft is supported by a system of radial and axial ball bearings. The shaft is mounted along its length in several journal bearings. The drive at the foot of the tower differs, depending on the application of the wind power system. For wind generators, a particularly high-ratio drive is installed with milled and hardened gears to which the generator is connected.

Automatic direction into the wind is provided by two wind vanes at the sides (R). Whenever the wind changes the wind vanes begin to rotate, driving the shaft (U) and the screw (W) through the worm gear and worm sheel (T). This rotates the bearing housing, which rests on a ring gear, until the wind wheel is again in the wind. The wind power plant head is accessible by means of a ladder through the framework. The tower height is determined by the local wind conditions, and is generally 20 to 30 m. The corner posts and the tower framework are made of heavy angle iron, with flat iron cross braces. The separate parts are held together with bolts. The corner posts rest in a concrete foundation which must be taken down to bedrock. /371

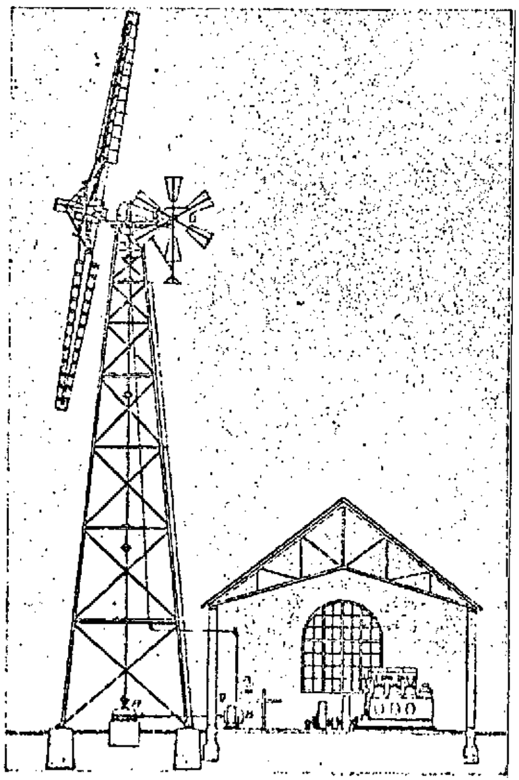

Figure 6. Schematic representation of a Lykkegaard wind power plant.

From the schematic representation of a Lykkegaard wind power plant, as is found particularly often in Denmark (Figure 6), it can be seen that the wind motor drives a generator, while there is also a Diesel system for calm periods and to cover peak loads.

The electrical system is relatively simple. The generator works into a battery which feeds the network. The current and voltage from the generator, as well as the electrical work generated, can be read from meters. In order to prevent backflow of current at low wind speeds, a La Cour relay is connected between the battery and the generator. The generator is a shunt machine which produces a current of 0 to 50 A at approximately constant voltage for a change in rotational rate of 400 to 800 RPM. The electrical system does not work fully automatically. In particular, the state of battery charge must be watched continuously.

In general, the Folding Sail wind power plants run well and produce power even at a wind speed of 4.0 to 4.5 m/s. Their maximum capacity is some 30 kW at 10 to 11 m/s. If we place the electrical power produced by the generator in a ratio to the power in a free air stream of 18 m diameter, then at a wind speed of 7 m/s we get a value of 0.22*. Figure 7 shows the power of such a system with a wind wheel of 18 m diameter as a function of the wind speed. As the wind speed increases above 11.4 m/s the /372
power no longer increases because the folding system normally goes into action then.

Generation in the Lykkegaard wind power plant depends very much on the existing conditions. At favorable wind conditions and heavy use the Folding Sail systems produce an annual work of

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* The quality of a wind wheel is characterized by the so-called power coefficient c_1, which is the ratio of the power at the wind wheel axle (effective power) to the total power present in a free air stream of corresponding diameter. From the theoretical investigations of Betz, c_1 can be 0.59 at best. We must then include the efficiency of the mechanical transmission (η_m) and the electrical efficiency of the generator (η_e). With the data above for the Lykkegaard wind force wheel, then, $c_1 \cdot \eta_m \cdot \eta_e =$ 0.22. The value of c_1 cannot be determined exactly because the mechanical and electrical efficiencies could not be found accurately.

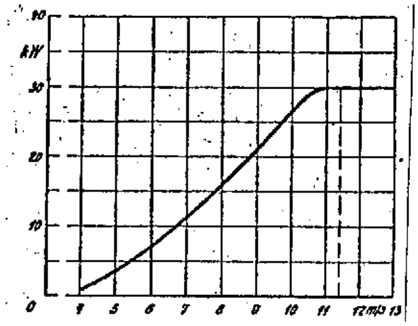

Figure 7. Power as a function of the wind speed.

50,000 kWh. According to measurements by La Cour at Vandrup, these systems could attain annual productions of 80,000 kWh if they could use all the wind above 4 m/s. The highest measured daily yield is some 600 kWh, which corresponds to an average power of 25 kWh*. The wind power plants are very robust in regard to maintenance. In general, it is sufficient to check the mechanical parts every two weeks.

The Lykkegaard company also produces wind pumping systems along with wind power plants. The basic rule of greatest possible simplicity and reliability applies particularly for these pumping plants, as the plants are usually established out of the way and are not maintained by experts. But such pump works are particularly suitable for wind power operation because all the incident wind energy can be converted immediately into pump work. Such systems are built up to delivery heads of 3.5 m and with screws up to 2.5 m diameter. The largest water screws of this type which have

* More detailed data on employment, generation and efficiency are summarized in the section on operating experience, which will be published as the conclusion in the next number of the journal.

been installed produce 4,000 m^3 water per hour at the nominal wind strength*.

The prices of the Lykkegaard wind power plants are given in Table 4. They refer to the wind wheel, a tower 20 m high, the vertical shaft and the gear for connecting the generator. These data are from 1939. Since then there has been a 70% rise due to war conditions. The same is true for the generator itself (Table 5).

Table 4. PRICE LIST FOR LYKKEGAARD WIND POWER PLANTS

Wind wheel diameter, m	18	16	14	12	10	7
Price of the wind power plant dKr	10 930	8 510	7 510	5 199	4 210	2 150
Erection costs dKr	1 080	820	700	540	450	315

Table 5. PRICES FOR DIRECT CURRENT GENERATORS WITH VOLTAGES OF 440/660 V, 220/300 V and 110/150 V FOR WIND POWER PLANTS (1939).

Nominal Generator Capacity kW	For Wind Wheel Diameter m	Price dKr
30	18	2740
25	16	2420
20	14	2420
15	12	1570
10	10	1170
5	10	850
5	7	610

* More details in the report of the W. E. V. and the R. A. W., "Wind Power Plants in Denmark".

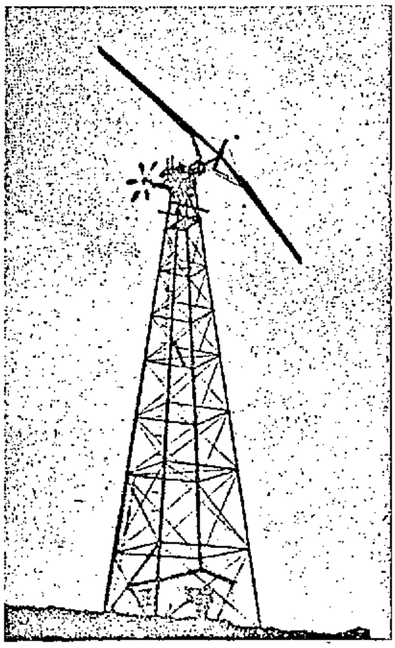

Figure 8. F. L. S. Aeromotor. 17.5 m wind wheel diameter, 50 kW power at 10 m/s.

The Smidth wind power plants (Figure 8), which are sold under the name of F. L. S. Aeromotor, work on a principle similar to that of the Lykkegaard systems. They generate direct current and feed a net through a battery. This is a distinctly high-speed system which makes up to 100 rpm at a sail diameter of 17.5 m. By comparison, the Lykkegaard wind power plants (La Cour sails) of the same diameter have a rotational rate of 20 rpm. The concept of high speed, which is decisive for the quality of a wind wheel, u/v (peripheral velocity of the sail tips/wind velocity) is 9 for the F. L. S. wind power plants. For the Lykkegaard plants we can set u/v about equal to 2.5. From German studies, a more favorable value for the speed is 4 to 5, although this is for a wind wheel with three vanes.

The sails of the F. L. S. wind power plants are made of special types of wood and protected against weathering with a special paint. The sails are strengthened by special metal fittings at the forward (luff) side. They are tilted somewhat to the rear (Figures 8 and 9) to compensate for the bending due to the wind pressure. This compensation occurs because the centrifugal force rises as the rotational rate does, attempting to straighten the vanes, thus counteracting the wind pressure. The folding system is at the side of the vanes away from the wind (lee side). It consists of a small auxiliary sail which in its normal position rests in the surface of the main vane. While the main vane is mounted solidly on its axis, the position of the auxiliary vane is determined by springs. These springs are preloaded for a wind pressure corresponding to a certain wind speed. When this wind speed is reached, the auxiliary vane is turned out of its normal position by the springs, so that the vane shape is distorted, producing a braking action. The braking system can also be operated from the ground. In this way, one can arbitrarily slow the rotational speed of the wind wheel or even stop it entirely. In addition, there is a braking system built into the drive connected to the wind wheel axle. This, too, can be operated from the ground with a rope. The braking and folding systems are operated simultaneously.

If the wind power plant is to be put back into operation after a stop, the braking and folding winches are turned back to their operating positions. But since the F. L. S. Aeromotor will not start up alone, it must first be set in motion. This can be done either with a special starting motor or by switching the generator to work as a motor. Then, when the wind wheel has reached a certain rotational speed, it is driven on by the wind. Then the machine returns from motor operation to generator operation. Starting from such an arbitrary stop can be done either by pressing a starting button or automatically. If the wind wheel stops during a calm, it is neither folded nor braked. Then it will start again as soon as the starting motor or the generator, switched to motor operation, is turned on. This is automatic. For this purpose, there is a small wind wheel on the upper housing. At a certain wind speed it closes a centrifugal relay which again connects the power to the starting motor and starts the wind motor. If the switchboard is at a large distance from the wind power plant, the braking system can be operated with an electrical motor controlled from the power central station.

The vanes of the wind wheel are installed on an axle which rests in a roller bearing, and which is hollow so that the folding mechanism can pass through. The axle of the wind wheel operates an F. L. S. drive which is provided with specially accurately milled gears to keep power transmission losses particularly low. The drive is oil-filled. Because of the very slight wear of the gears, however, it is seldom necessary to change the oil. /373

The drive operates the DC generator, which is installed at the top of the tower, through an elastic coupling. This generator has special exciter windings so that it can follow the rotational speed of the wind wheel with good efficiency. The current is taken off by a set of contact rings, and is conducted from there to the base of the tower and, if necessary, on to the central station, which has a shunt controller to regulate the generator voltage and an overcurrent relay to protect the generator against overload. In the new designs a La Cour relay is also installed. This switches the generator off from the net if reverse current occurs; that is, if the generator voltage drops below the line voltage, so that the generator takes current from the line and acts as a motor. The generator is again connected if its voltage has risen enough so that it can produce current again. A back-wind relay is installed to protect against sudden changes of wind direction. It goes into action if the wind comes from behind, operating a brake.

The electrical system is completed by a voltage regulator which automatically stops charging when the battery has reached the desired state of charge. The central station has the necessary measuring instruments to check the operation of the wind power plant, such as voltage, current, and power meters.

The wind wheel mount, the drive and the generator are set on a framework which is arranged so that it can be turned about the top of the tower. The turning is done by two wind vanes at the left and right of the drive. They respond to changes in the wind and place the wind wheel perpendicular to the wind direction. In a storm, the wind wheel remains in the wind, but the folding and braking system operates. The tower for the F. L. S. wind power plant is either iron or reinforced concrete. The iron tower consists of four structural iron columns mutually braced. Below the tip of the tower is a platform so that one can get to the wind motor head over a stairway. The construction company has had good experience with this tower design.

The shortage of iron in Denmark, however, has had the result that a large part of the F. L. S. Aeromotors had to be build with reinforced concrete towers. Here problems arose initially with respect to the strength when passing through resonance. These were attacked at once. On the other hand, the reinforced concrete tower has the advantage that it fits better into the landscape (Figure 9) and offers more protection against bad weather for climbing, because the stairway is inside the tower. The concrete tower has a gallery at the top, from which one has access to the wind motor. In comparison to the iron tower the concrete tower also has the advantage that the maintenance costs are small,

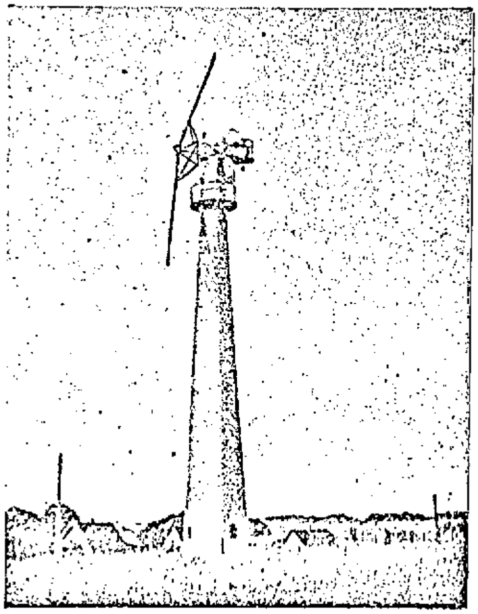

Figure 9. F. L. S. Aeromotor, concrete construction. Tower 24 m high, wind wheel 17.5 m.

while the iron tower must be painted at regular intervals.

The Aeromotors built so far by the F. L. Smidth company have all been direct current, with one exception. The following solution is planned for alternating current: The DC generator at the top of the tower will provide current to a motor driving an AC generator at the food of the tower. In this way the generator itself remains connected to the transformer even at low wind strength and correspondingly low rotational rate, as backflow of current is prevented by a relay in the AC circuit. Conversely, power is fed to the line as soon as the nominal rate of rotation is reached. An overload relay is planned.

The F. L. S. Aeromotors begin to produce current for the battery at a wind speed of 5 m/s. Their nominal capacity is 50 kW at 10 m/s, but the generator can be severely overloaded.

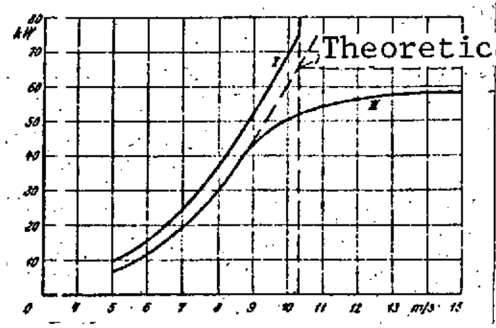

Figure 10. Power from an Aeromotor as a function of the wind speed (wind wheel diameter 17.5 m).

In strong winds, for instance, the 17.5 m Aeromotor can generate 70 kW even for a considerable time. According to data from the F. L. Smidth company, the efficiency coefficient c_1 reaches the considerable value of 0.47 at 9 m/s. Consideration of the mechanical and electrical losses ($c_1 \cdot \eta_m \cdot \eta_e$) gives a value of 0.34 at 10 m/s wind speed. Figure 10 shows the power of the F. L. S. wind power plant as a function of the wind speed. The vanes fold at a wind speed of 10.2 m/s.

There are only a few results about generation of the F. L. S. Aeromotors. Originally, a yearly production of 0.2 to 0.3 million kWh was stated for the design with 17.5 m wind wheel diameter. These figures are far too high and, as will be shown in the concluding part of this work in the next number of the journal, are due to very inaccurate observation of the wind frequency. Nevertheless, such an F. L. S. Aeromotor has already attained a daily production of 1,400 kWh, corresponding to an average power of 57.5 kW, under particularly favorable wind conditions.

For the present, there are only approximate data on the costs of F. L. S. wind power plants. According to these, a 17.5 m wind power plant with the electrical portion, but without the battery, would amount to 55,000 dKr.

The electrical equipment in the Lykkegaard and Smidth wind power plants comes mainly from the electrotechnical company of T. B. Thrige, Odense, which has years of experience in the area /374
of generator design for wind power plants. In the past 25 years it has provided the electrical equipment for more than 100 wind power plants. The Thrige generators for wind power plants are designed for charging voltages of 440/600, 220/300, 110/150, and 65/90 volts. They are arranged so that they can work into a battery. In normal designs they are furnished up to a capacity of 30 kW. These are shunt-wound machines which are matched to the particular load conditions which occur with wind power plants. They work in a certain range of rotational speed. The lower limit of the range is the speed of the wind wheel in weak wind, so that hardly any power can be produced. The upper limit is the speed in strong wind where the generator reaches its nominal capacity. In general, the Thrige generators are designed so that the upper limiting speed is twice the lower one. Any greater enlargement of this range would run into problems.

Small Systems

Since small wind power systems have been used for a long time in the United States of America to produce power in out-of-the-way places*, the Danish engineering and construction company Getler, Kalundborg, has recently brought out several designs of small wind power systems with wind wheel diameters of 2 or 3 meters (Figure 11). Their design is matched particularly to the Danish wind conditions. Here the generator, which is mounted at the top of a tubular stand, is directly driven by a propellor. The generator is designed for voltages from 6 to 220 V and for a power of 125 W, 330 W, or 1 kW. According to data from

* D. Stein, Advances in utilization of wind power for generating electricity. Elektrizitätswirtschaft 40:268-271 (1941).

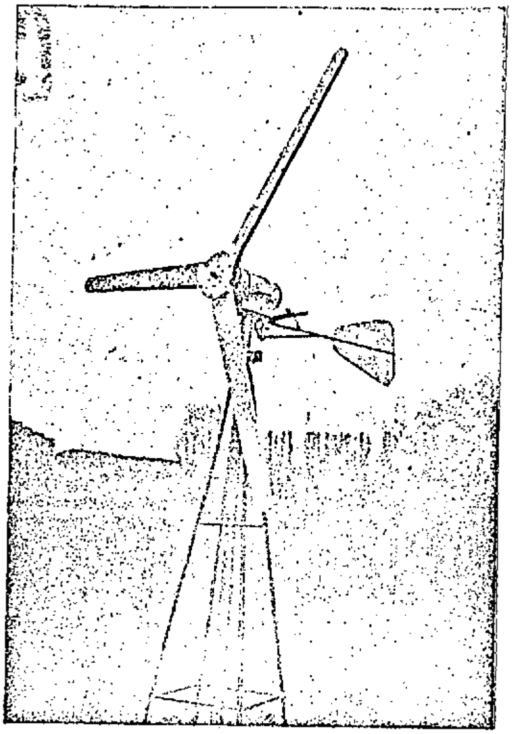

Figure 11. Small wind power plant, Getler design.

the construction company, the largest design is intended to produce up to 1,100 kWh annually. The small wind power plant is intended primarily for lighting farms and houses which are not connected to a power line. Automobile starter batteries can be connected to the system for storage. Considering the low operating costs, the price per kWh will be very favorable, in the opinion of the builder. Of course, it must be considered that the battery will soon be exhausted in long calms and then the power supply will be interrupted if there is no reserve system. But a reserve system — only a producer gas system was considered — cannot pay off in such small systems.

It is interesting that even the smallest wind power systems of 6 V working potential are considered to be high-power systems, and must, correspondingly, be installed by a certified installer.

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